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- *Title:* Technology Showcase: Integrated Monitoring, Diagnostics and Failure Prevention. Proceedings of a Joint Conference, Mobile, Alabama, April 22-26, 1996.

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AN HISTORICAL VIEW OF THE MFPT SOCIETY

Henry C. Pusey
Society for Machinery Failure Prevention Technology
4193 Sudley Road
Haymarket VA 22069-2420

Mechanical failures are a pervasive fact of life in our society. Ranging from the failure of small items that all of us have experienced and that many of us take for granted, to the failure of a large complex structure that often becomes front page news, they have undesirable consequences for our society. The large ones many times cause loss of life or cause serious injury to many people. The minor ones sometimes also cause loss of life or injury, and they always cause frustration and anger on the part of the one to whom they occur. Always they cause loss of valuable material, and have undesirable social and economic consequences.

... Elio Passaglia, Executive Secretary MFPG, 1976

Abstract: This paper provides a general overview of developments and progress in mechanical failure prevention technology, primarily over the last three decades. It is a condensed version of a paper presented at a luncheon of the ASME Reliability, Stress Analysis and Failure Prevention Committee at the 1995 Design Engineering Technical Conferences. The principal reference sources used are the proceedings of the 49 conferences of the Mechanical Failures Prevention Group (MFPG), now the Society for Machinery Failure Prevention Technology (MFPT). Since many technical disciplines are involved in this complex technology, an attempt is made to place mechanical failure prevention in perspective. Discussion of the evolving technology is presented under four topic areas that serve to cover most of the elements of this broad-based field. These topics are Diagnostics and Prognostics, Failure Analysis, Life Extension and Durability, and Sensors Technology.

Key Words: Condition monitoring; diagnostics; failure analysis; failure modes; maintenance; mechanical failure; oil analysis; vibration analysis

INTRODUCTION: The above quotation is taken from the Introduction to the Proceedings of the 20th Meeting of the Mechanical Failures Prevention Group (MFPG). Dr. Passaglia, who was then Chief of the Metallurgy Division of the National Bureau of Standards (NBS), assumed the responsibilities of MFPG Executive Secretary after the merger of the MFPG with the NBS Failure Avoidance Program in the early 1970s. MFPG 20 was a milestone event. Sponsored by seven government agencies and ASME in May 1974, the meeting was designed to explore the various aspects of mechanical failures with the purpose of "defining the problem". The symposium organizers chose to examine the technology from the aspect of failure modes, failure consequences and the implication of failure with respect to action by the technical community. The conference program was planned accordingly; the result was a collection of informative and thought provoking papers.

Failure of machinery, equipment or structures has even greater implication today than it did twenty years ago. As our society becomes more and more mechanized, as demands on performance become more exacting, and as our technology becomes increasingly complex, each mechanical failure reaches greater significance. In terms of the economy of the country, mechanical failures represent a cost of billions of dollars every year to industry, the government and the general public. Improved public safety, an area of paramount concern, may be achieved by a higher level of understanding of the mechanical failure process coupled with innovative techniques for failure avoidance, especially when using new or emerging materials in the design of structures and equipment.

Failure prevention technology is complex and clearly involves a wide range of technical disciplines. Any in-depth history of failure prevention would result in numerous books, each covering one or more of the technologies that relate to failure and its prevention (e.g. materials science, tribology, vibration analysis, etc.). One can only examine advances in failure prevention from a broad perspective. That is the purpose of this paper. Progress in selected areas of mechanical failure prevention is assessed, particularly over the last quarter century. The references used are primarily from the proceedings of the MFPG conferences held since its inception in 1967 through its change of name to The Society for Machinery Failure Prevention Technology (MFPT) in mid 1994 and MFPT 49 in April 1995.

FAILURE PREVENTION IN PERSPECTIVE: The need to prevent failures has been with us since man began inventing functional gadgets. There has always been an unwritten rule that each gadget should operate as long as possible without breaking or malfunctioning. Taken as a whole, failure prevention is considered by many to be a technology. The definition of technology is the application of science. Thus mechanical failure technology could be defined as the application of science to mechanical failure processes. Understanding the failure process may require a study of what is failing, the nature of a practical failure and the sequence of events which leads to failure. One must then describe the failure process in terms of design or material variables.

Early in their history, the MFPG recognized that this is a complex process and that there are many ways to prevent mechanical failures in service. These actions include but are not limited to

- developing better design techniques.
- improving reliability predictions.
- providing more complete materials information.
- better understanding of the failure process.
- improved quality control.
- effective maintenance.
- improved diagnostics.
- cleanliness.
- lubrication/wear reduction.
- improved failure analyses.
- feedback of analysis results.

By their sixth meeting the MFPG Steering Committee recognized that increasingly large numbers of interested persons were attending two-day symposia. Papers were given and discussions heard covering almost all identifiable aspects of mechanical failures. Although these meetings provided the best forum for information dissemination, they did not foster structured pursuit of specific mechanical failure prevention tasks. To meet this need Technical Committees were organized on **Detection, Diagnosis and Prognosis, Mechanisms of Failure, Design (including Testing),** and **State-of-the-Art and Applications**. With the objectives of the MFPG remaining essentially the same, the MFPG committee structure was modified slightly over the years in response to changing emphasis. The latest committee designations are **Diagnostics and Prognostics, Failure Analysis, Life Extension and Durability** and **Sensors Technology**. For convenience, these titles are used as topic areas for the material presented in this paper.

DIAGNOSTICS AND PROGNOSTICS: *Diagnosis* is the art or act of identifying a condition from its signs or symptoms. *Prognosis* is the art or act of predicting a future condition on the basis of present signs and symptoms. Any method used for identifying incipient failures and/or predicting ultimate failure of materials, structures or systems would fall within the scope of the Diagnostics and Prognostics Committee. The reader should note that there are overlapping areas of interest among all of the technical committees. For example, predictive maintenance, a subset of condition-based maintenance, involves diagnosis and prognosis. At the same time, effective application of maintenance philosophy is a proven technique for extending the life of machinery. In this section, the most commonly used techniques for diagnostics are discussed, the issue of prognostics is addressed and an attempt is made to assess our current capabilities for failure prediction.

Diagnostic Methods: Vibration signal analysis and oil analysis are treated separately as techniques for diagnosing condition and fault mechanisms in machinery. Other selected nondestructive testing and evaluation methods that are applicable to materials, structures or machinery are then described.

Vibration Analysis: It is not known when vibration signature analysis was first used as a diagnostic tool. It is clear that by the time the MFPG was organized in 1967, machinery health monitoring techniques using vibration signatures had already been in use for a number of years. The minutes of the first MFPG meeting indicate that the technical presentations all related in some way to diagnostics involving vibration. The theme of the sixth meeting was *Detection, Diagnosis and Prognosis (DD&P)* as well as that of a number of meetings that followed. With a few exceptions, DD&P was a part of the program at all MFPG meetings and vibration was always very much in evidence as a diagnostic tool.

The tenth MFPG meeting was organized with specific emphasis on the utility of vibration analysis methods in mechanical failure prevention. A presentation on time series analysis techniques clearly showed the usefulness of analytical techniques for comparing differences in vibration waveforms. The discussion at that meeting showed lack of agreement on how these techniques could be applied to machinery condition monitoring. Five papers were devoted to the use or trial of automated vibration monitoring and diagnostic systems for aircraft gas turbine engines, ships' machinery, helicopters, commercial jet aircraft, and internal combustion engines. Advantages and limitations of the various systems were discussed. At that time there were some

limitations with respect to available instrumentation as well as on the capability to identify the faults in and condition of machinery so that effective maintenance planning could be achieved.

By the time of MFPG 44 fifteen years later it was evident that instrumentation capability had increased dramatically, but that techniques for fault diagnosis had evolved more slowly. The tools were still more advanced than the techniques. Eshleman [1] addeessed this issue in some detail and examined three technical areas that must be addressed for effective fault diagnosis using vibration; these are *condition and fault mechanisms*, *modification of signal transmission paths* and *signal analysis*.

The 1994 proceedings (MFPG 48) contains several papers that reflect significant progress in the application of vibration analysis to diagnostics. Specific advances were reported on helicopter transmission fault detection and classification, alarm threshold settings for vibration monitoring of rotating machinery and pattern classification of vibration signatures using neural networks. Some preliminary ideas on the application of smart structures in conjunction with vibration signature analysis for on-line machinery health monitoring were presented. It will be interesting to see how the use of this technology evolves.

Oil Analysis: All machinery requires lubrication to minimize wear. This includes various engines (internal combustion, diesel, turbojet, etc.) and their components (transmissions, gear boxes). Everyone knows that the oil must be changed in automobiles at regular intervals to extend the life of the engine. This routine maintenance action is necessary because the oil gets dirty. Dirty, *worn out* oil not only does not lubricate well, it actually increases engine wear. Why? What is this *dirt* in the oil? How can information about it be used to ensure that engines operate safely and to identify engine components that will fail with potentially catastrophic results unless corrective action is taken? The process is called *oil analysis*, a proven diagnostic tool for mechanical failure prevention.

At the second MFPG meeting in June 1967, Ward [2] described a Navy spectrometric oil analysis program initiated in 1955. The goal was to find out whether the concept employed by the railroads for determining the condition of diesel engines by analyzing used oil samples could be applied to aircraft engines. The Bureau of Aeronautics felt that if these techniques could be applied, inflight failures could be minimized, extension of engine operating intervals could be justified and reductions in engine overhaul costs could be achieved. This was not a new idea, but the concept had been restrained for some time by concern over the many factors which could work against development of successful techniques. Consider that the wide variety of engines in service, the many sources of wear metal contamination, the many sources of lubricating oil base stock, the necessity for development of metallic contamination threshold limits, the time and cost involved in sample analysis and the sample handling and data communication problems must all be dealt with to achieve success. They were able to handle these and other problems successfully and in 1958 some positive results accelerated the program. By 1967, the Navy was working jointly with the Army and Air Force. The results were very impressive as evidenced by the very successful DoD Joint Oil Analysis Program (JOAP) coordinated by the Technical Support Center at Pensacola, Florida.

The use of oil analysis, as reported at the MFPG conferences, has been an invaluable diagnostic tool over the years. Application of the technique to internal combustion engines was discussed at MFPG 12 and to commerical aircraft at the 14th and 16th meeting. Oil analysis was the theme of MFPG 16 and advancements in both techniques and analysis equipment have been faithfully reported in the proceedings since then. At MFPG 48 the Naval Research Laboratory [3] reported on a real time, on-line, optical oil-debris monitor that is expected to provide a cumulative record of the health of engines and gear boxes as well as advanced warning of catastrophic failure.

Nondestructive Testing and Evaluation (NDE): NDE in general is the technology of measurement, analysis and prediction of the state of material systems for safety, reliability and assurance of maximum lifetime performance. It is an old technology (more accurately a set of technologies), yet it is only in recent years that engineers and managers have awakened to the true importance and great potential of NDE. Some NDE test technologies that can be effectively applied to diagnostics include acoustics, microscopy, optics, thermography, electromagnetics and radiography. The capabilities of these NDE methods as diagnostic tools for equipment and structures have increased significantly with the rapid development of advanced hardware and software. Although a detailed discussion of progress in each NDE area is not possible, it is useful to describe how some of these methods are used for fault diagnosis.

Acoustic Methods: *Tap testing* is probably the simplest, most common and inexpensive form of acoustic inspection. The inspector taps the surface of the test structure and evaluates the sound that is generated. He either listens directly to the sound or uses a specially designed receiver to analyze the sound and compare the response with one from a non-defective part.

The *acoustic emission* (AE) technique is a method whereby sound waves emitted from a growing crack or flaw in a structure are detected. These signals are then evaluated to determine the nature of the damage. The advantages of AE are that it offers global monitoring capability and real time information as to the state of damage. The problems with the technique arise from the complexity of sound propagation in solid structures which makes interpretation of the AE in terms of structural damage difficult.

The *acoustoultrasonic* (AU) technique was devised to assess diffuse discontinuity populations of the mechanical properties of composites and composite-like materials. This NDE method, also known as the *stress wave factor* technique, has been used to evaluate fiber reinforced composites, adhesive bonds, lumber, paper and wood products, cable, rope and human bone. The AU technique has been demonstrated to be sensitive to interlaminar and adhesive bond strength variations and has been shown to be useful in assessing microporosity and microcracking produced by fatigue cycling. The AU method belongs to a class of techniques that includes tap testing, dynamic resonance and structural damping measurements. These are in addition to more directly related techniques like acoustic emission and pulse echo methods.

Acoustography is a process of forming ultrasonic images in a manner similar to X-ray fluoroscopy, using a detector screen that converts ultrasonic energy directly into a visible image. A full field imaging method, *acoustography* may be used to rapidly screen parts for discontinuities. *Acoustic holography* is yet another useful NDE method which was first

discussed by MFPG participants at their ninth meeting. This method involves only the recording of a hologram and its image reconstruction. Thus, unlike optical holography, the additional interferometry step (after stressing the material) is unnecessary to produce an image depicting internal anomalies. The reconstructed images from acoustic holograms, however, do not possess the high resolution image quality of the shorter wavelength optical holograms.

Vibration analysis is often considered to be an acoustic method. This is in part because sound produced by machinery can be used in the same way as vibration for machinery diagnostics. After all, the sound radiated from machinery is produced by the vibration of the machine. There have been technical discussions at MFPG and other conferences about whether vibration or acoustic signal analysis is most useful. Either can be used effectively. The simplest way to use sound is by an experienced machine operator who will know that something is wrong when his machine sounds different than it normally does.

Infrared Analysis: Infrared or thermographic analysis provides a high-resolution, non-contact means of monitoring the condition of electrical and electromechanical equipment, roofing and wall insulation and oven refractories. Infrared scanners, similar in appearance to video cameras, detect differences in surface temperatures and highlight those differences in black and white or color images that are displayed on a television screen. These images, called thermograms, are used to analyze patterns of heat gain or loss. Infrared analysis is an effective predictive maintenance tool because mechanical or electrical breakdowns are often preceded or accompanied by changes in operating temperatures. This information can be particularly important in electrical machinery where circuits and connections may show no visible signs of deterioration until moments before a complete failure.

Motor Current Signature Analysis (MCSA): MCSA provides a nonintrusive method for detecting mechanical and electrical problems in motor driven rotating equipment. The method is the development of Oak Ridge National Laboratory [4], as part of a study on the effects of aging and service degradation of nuclear power plant components. The basis for MCSA is the recognition that an electric motor driving a mechanical load acts as an efficient, continuously available transducer (the motor can be either AC or DC). The motor senses mechanical load variations and converts them into electric current variations that are transmitted along the motor power cables. These current variations, though very small in relation to the average current drawn by the motor, can be monitored and recorded at a convenient location away from the operating equiment. Analysis of these variations can provide an indication of machine condition, which may be trended over time to provide an early warning of machine deterioration or process alteration.

Prognostics: The words *prediction* or *prognosis* appear in a number of titles of papers in the MFPG proceedings. The *prediction* papers usually deal with mathematical models for fatigue life estimation, stochastic models for cumulative damage or trending algorithms of one sort or another. Usually these papers report useful work that is consistent with the definition of *prediction* as *a way to establish beforehand the expected value of some parameter at a definite future time*. However, these methods have not yet been effectively applied by the predictive maintenance community for on-line prognostics.

Some ideas have shown promise. Dunegan [5] suggested that the combination of acoustic emission and linear fracture mechanics can provide quantitative information regarding structural failure. Wicks [6] proposes that experimental modal analysis techniques can be used as a tool in predictive maintenance programs. Modal models of a given machine provide a baseline from which trends may be monitored and evaluated. At MFPG 47, this same idea was examined with respect to structures [7].

Salter [8] stated in 1978 that on-vehicle computing instrumentation technology offers new capabilities to improve life-cycle reliability through prognostics. Prognosis enables the selection of the best time for maintenance while reducing inspection requirements, vehicle breakdowns and secondary failures. He suggested that his program enables an improved user confidence while maximizing the productivity of scarce maintenance resources. The program requires a microdata system that can automate condition trend analysis using a technique that Salter calls *Geriometry*, a process which measures the causes of vehicle degradation, whereas all other maintenance techniques measure effects. It is not clear whether this idea was made to work, but the premise was good. Effective prognosis is important to maintenance management. Some technique is necessary to choose the time for maintenance which will minimize maintenance costs while achieving a desired reliability and availability. The technique must be quantified in terms of measurable parameters. The precision and variance with which these parameters describe the subsystem life must yield decision criteria within close confidence limits. The rationale for prognosis as an effective technique for maintenance is somewhat subjective, since data to prove the contention do not yet exist. It is anticipated by many persons in the maintenance field, however, that a number of benefits will accrue with the implementation of reliable prognosis methods. For the most part, however, the MFPG papers with *prognosis* in the title are lacking in information on effective prognostic techniques. The remaining life of a machine or component must be based upon wear, the environment, and the history of stress cycles in the machine. These factors must also be considered when establishing its current condition. Only after the current condition of a machine is known can meaningful life estimates be made. Information about current condition can also be used to evaluate the effects of changes in components and wear in order to assess whether or not machine life can be extended. The techniques of prognosis involve diagnosis, condition models, and failure models. Failure models that predict time or cycles to failure have been available for materials and simple structures for years. But no failure models have been developed for factors other than stress and strength.. The development of failure models and the data to implement them is a major challenge for the maintenance community.

FAILURE ANALYSIS: The first name for the present MFPG **Failure Analysis** Committee was **Mechanisms of Failure**. The original broad objective of the Committee was to coordinate all aspects relating to the modes and mechanisms of failure as they pertained to the overall goal of mechanical failure prevention. Among other things, the pursuit of this objective involved standardization of terminology and the establishment of interrelationships among causes, modes and results of failure. The scope of the current Committee not only covers mechanisms but also methods of failure analysis and the application of *lessons learned* from failure analysis results. Collins [9] defines *mechanical failure* as *any change in the size, shape or material properties of a structure, machine or machine part that renders it incapable of performing its intended*

function. He defines a *failure mode* as *the physical process or processes that take place or combine their effects to produce failure*. Collins lists and defines 23 failure modes, five of which have several sub-categories.

Beginning with the early MFPG conferences failure modes were discussed extenxively. The important modes of fatigue, wear and corrosion were the topics for several meetings. The eleventh meeting was devoted exclusively to an examination of *mechanical fatigue* as a critical failure mechanism. Of the MFPG papers relating to *wear*, the majority deal with minimizing wear by design of surface finish or by the use of lubricants and coatings. A number of papers in the proceedings concern wear problems and solutions for specific critical components such as bearings. This is at least in part due to the extreme complexity of the wear failure mode. At least nine subcategories of wear have been defined and more than twenty variables are involved in the wear process. Progress in wear reduction is therefore better demonstrated by reporting on specific solutions to the problem. For example, MFPG 13 was concerned with the standardization of surfaces to minimize wear (or fatigue) failure. The 16th and 30th meetings were devoted to lubricants and lubrication. All of the 23rd and part of the 37th meetings dealt with coatings to improve wear resistance.

Corrosion is another important complex failure mode. As with wear, many variables are involved in the corrosion process that relate to environmental, electrochemical and metallurgical aspects. There are eleven recognized direct subcategories for corrosion; in addition, *fretting corrosion*, *stress corrosion*, *corrosion wear* and *corrosion fatigue* may be regarded as special synergistic failure modes. The 15th and 17th meetings were concerned in great part with various aspects of corrosion. The objective of MFPG 15 was to examine the state-of-the-art in the study of various corrosion mechanisms. The papers at MFPG 17 addressed environment-sensitive failure modes such as *stress corrosion cracking* and lubrication failure which can, among other things, lead to corrosion.

Cavitation as a damage mechanism was the topic for discussion at MFPG 19, with more than a dozen excellent papers covering various aspects of the problem. Peterson [10] provides a detailed discussion on how this complex, imperfectly understood phenomenon can lead to mechanical failure. M. B. Peterson [11] pointed out that the literature has been somewhat confusing concerning the *fretting* mode and proceeded to clarify the phenomenon. The theme of MFPG 35 was "Time-Dependent Failure Mechanisms and Assessment Methodologies". The principal failure modes covered were fatigue, stress corrosion cracking and creep. The papers dealt with these mechanisms in connection with a variety of applications, including gas transportation cylinders, concrete, wood and ceramics. This is consistent with the MFPG objective to examine problems related to failure of structures and machinery and to develop realistic approaches to their solution.

The analysis of the cause of failure is important to the failure prevention effort. The most vivid examples are failures that cause catastrophic accidents resulting in loss of life, such as air or rail crashes. The National Transportation Safety Board (NTSB) investigates all such accidents as a matter of routine [12] with the goal of avoiding similar failures in the future. Such cases are extraordinary, but it is always useful to determine the root cause of failure when it is

economically feasible to do so. The general topic of the 8th MFPG meeting was an examination of "Critical Failure Problem Areas in the Aircraft Gas Turbine Engine." The papers at this conference were not formal failure analyses. Rather, they report on causes of failure as determined during required engine repair or routine overhaul and maintenance. Failures in internal combustion engines were treated in a similar way at MFPG 12. Bennett [13] presented an excellent paper at MFPG 20 on the importance of analyzing service failures, what can be learned from the analyses, and how to use the information that is obtained. The theme of the 21st MFPG meeting was "Success by Design: Progress Through Failure Analysis" could be considered a response to Bennett's paper. The 21st MFPG Proceedings clearly demonstrates the value of the feedback of information gleaned from service failures into the design process. This idea is strongly supported in papers by Rieger et al [14], Pond [15] and Natishan [16].

LIFE EXTENSION AND DURABILITY: The current **Life Extension and Durability Committee** was formed only recently. Its organizational meeting was held in April 1994 at MFPG 48, thus its scope and mission is still evolving. The terms *durability* and *life extension* need some clarification. Ideally, a design engineer establishes some achievable goal for the expected service life of the system he is designing, then proceeds to design the system to meet that goal. The durability of the system is some measure of how well the system survives without failures throughout its expected service life, while functioning effectively with little or no loss in efficiency. If as a result of a special design effort, the system is capable of functioning beyond its normal expected service life, the designer will have achieved life extension by design. Life extension can also be achieved through the use of on-line condition monitoring systems capable of detecting imminent failure in time to avoid failure through effective maintenance procedures. Properly implemented, the condition based maintenance approach can ensure that machinery, for example, will operate at peak efficiency, not only through its normal expected service life but well beyond. Based on the present state of the technology, it is reasonable to assume that designers are not able to estimate the service life of their system with any degree of accuracy. Instead, it is suggested that engineering designers will develop an environmental life cycle profile for the system they are designing and use their knowledge of materials and failure modes to develop the most durable and reliable system that they can.

At MFPG 27, durability and life extension was examined with respect to the durability of consumer products. In this case, durability involves both technical and economic considerations. Thus the major problem of design is to increase durability within the constraints of economics. Lund and Denney [17] offer keen insight on the issues involved in extending the life of consumer products. Other papers dealt with product life testing methods and reasons for being concerned about improved product performance, such as materials conservation, waste reduction and product safety. The 27th meeting also included a panel discussion on the topic *Can and Should Product Life Be Extended*? From the published introductory remarks by the panelists, it appears that the debate was lively with respect to both aspects of this question.

Active service life extension programs are ongoing in the nuclear power, aircraft and petrochemical industries, as well as for bridges and highways. Manufacturers recognize the wisdom of extending the life of their machinery. A few papers at MFPT 49 dealt with life

extension, through both design and maintenance procedures. It is expected that presentations on these topics will be much in evidence at future MFPT conferences.

SENSORS TECHNOLOGY: Sensors are key elements of data acquisition systems and, since measurement has always been an important part of mechanical failure prevention efforts, sensor technology has been of prime interest to the MFPG since its inception. Whether the problem is fault detection and diagnosis, structural inspection for defects or experimental life estimation procedures, the use of sensors is usually required. For this reason it is the role of the experts on the Sensors Technology Committee to provide technical guidance for other MFPT committees on linking failure modes to appropriate sensing technologies.

In 1968, Janowiak [18] suggested that sensors used for the diagnosis of mechanical failures must be adapted to physical effects resulting from known failure modes in mechanical systems. He pointed out that a vast sensor technology exists which is applicable to diagnostics and that a comprehensive search for sensors to bridge the interface between the mechanical and diagnostic systems was required. It is not certain whether such a search was conducted in an organized way, but a search of the proceedings reveals that at least twenty different sensor applications are reported at MFPG 6 through MFPG 36; many of these were very unusual. This is evidence that innovative engineers can develop sensors to measure almost any failure related parameter that may emerge. There are other examples in later proceedings. Floyd [19] discussed four types of sensors useful for condition monitoring. One type was an advance warning ice detector for the inlet stages of gas turbine engines, a very critical problem. Redden [20] described an intriguing smart integrated microsensor system capable of real time fatigue analysis of strain data. The use of embedded fiber optic probes to measure temperature through-the-thickness of composites was described by Whitesel and Sorathia [21]. Some interesting comparisons were made on the use of laser vibrometers, parabolic microphones and accelerometers for rolling element bearing diagnostics [22]. Several other new or unique sensor developments were reported in MFPG 48 and MFPT 49 [23-29]. It is reasonable to conclude that some of the greatest advances in the mechanical failure technology arena over the past 25 years have been in sensor development.

CLOSURE: A limited discussion of mechanical failure prevention technology as reported in the proceedings of the MFPG meetings since 1967 has been attempted. Nearly 1000 papers are published in these proceedings, in whole or in part, over the 28 year period. Some of the earlier proceedings provided only abstracts or synopses for several of the papers. These proceedings represent a significant body of work in a number of different technical areas all tied together by the common thread of failure prevention.

Diagnostics and Prognostics is prominent in the proceedings, in part because it is a "hot topic" in both the public and the private sector. Successful Condition Based Maintenance (CBM) programs using D&P technology can have a very high payoff, both technically and economically. The majority of U.S. industrial firms view effective maintenance as a fundamental prerequisite to economic success and are currently using some type of Predictive Maintenance (PdM), a major component of CBM.

The MFPG/MFPT proceedings clearly indicate significant improvements in condition monitoring and diagnostics capabilities over the past 25 years. Improved techniques developed by creative engineers, coupled with marked advancements in diagnostics hardware and software have resulted in more successful PdM efforts. In many cases, faults can be detected early, the location of the fault can be identified and appropriate maintenance can be scheduled in time to avoid catastrophic failure. More and more PdM systems are automated and many employ a combination of diagnostic techniques. In many cases, time to failure can be predicted with reasonable accuracy. However, prediction of time to failure should not be confused with prediction of remaining service life. Although some progress has been made in prognostics, much work remains to be done on the development of life estimation methods. The difficulty of predicting service life increases with the complexity of the system and the number of potential failure modes.

Procedures for conducting failure analyses are well established but are usually relatively expensive for systems with any degree of complexity. Natishan [16] points out that there are many situations in which component failure has little or no impact on safety, reliability or economics. Therefore, the cost of doing a failure analysis must be weighed against the benefits to decide whether or not an analysis is justified. As a general rule, in all cases where failure has a major impact on safety or operations it is essential that the cause of failure be determined.

This paper began with a quotation from the proceedings of MFPG 20. Six papers from that proceedings [30-35] addressed the broad implications of mechanical failures for the divergent segments of our society. These papers provide useful perspectives on mechanical failure that, taken together, define the national scope of the failure prevention problem and clearly show that the impact of such failures on our society is very broad. Almost all segments of the public and private sectors are concerned in one way or another with failure prevention. Beyond that these papers strongly suggest that solutions will be found more quickly through mutual cooperation, better communication links and effective mechanisms for interchanging technical information on mechanical failure prevention technology.

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